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Relationship between ultrasonic velocity and compressive strength for high-volume mineral-admixtured concrete

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Abstract

Ultrasound is used to evaluate the compressive strength of concrete with mineral admixtures. In addition, the relationship between ultrasound velocity and compressive strength of concrete are evaluated. High-volume fly ash (FA), blast furnace slag (BFS) and FA + BFS are used as the mineral admixtures in replacement of Portland cement (PC).

Compressive strength and ultrasonic pulse velocity (UPV) were determined at the 3-, 7-, 28- and 120-day curing period. Both compressive strength and UPV were very low for all the levels of mineral admixtures at an early age of curing, especially for samples containing FA. However, with the increase of curing period, both compressive strength and UPV of all the samples increased. The relationship between UPV and compressive strength was exponential for FA, BFS and FA + BFS. However, constants were different for each mineral admixture and each level replacement of PC.

Keywords: Ultrasound pulse velocity; Compressive strength; Fly ash; Blast furnace slag

1. Introduction

At present, the investigation of nondestructive testing techniques [1] is a very popular subject. The ultrasonic method [2,3] is one of the nondestructive testing techniques and is frequently adopted for evaluating the quality of in situ concrete structures.

The ultrasonic pulse velocity (UPV) technique is used as a means of quality control of products which are supposed to be made of similar concrete: both lack of compaction and a change in the water/cement ratio would be easily detected. The technique cannot, however, be employed for the determination of strength of concretes made of different materials in unknown proportions [4]. It is true that there is a broad tendency for concrete of higher density to have a higher strength (provided the specific gravity of the aggregate is constant) so that a general classification of the quality of concrete on the basis of the pulse velocity is possible [5]. Some figures suggested by Whitehurst [6] for concrete with a density of approximately 2400 kg/m^3 are given as excellent, good, doubtful, poor and very poor for 4500 m/s and above, 3500–4500, 3000–3500, 2000–3000 and 2000 m/s and below UPV values, respectively. According to Jones and Gatfield [5], however, the lower limit for good quality concrete is between 4100 and 4700 m/s.

The measurement of the ultrasonic compressional wave velocity has been used for a long time to evaluate the setting and hardening of cementation systems [7–16].

Admixtures, such as fly ash (FA) and blast furnace slag (BFS), are used as replacement for cement for improving the mechanical properties, decreasing the rate of hydration, decreasing the alkali aggregate reactivity and decreasing the permeability of concrete. However, their effects on the ultrasound and the relationship between compressive strength and UPV have received little attention.

The relative performance of the FAs in concrete depends on the brand of cement used. In addition, the age of the test is an important factor influencing the relative performance of the various cementing materials [17].

Due to the rapid economic development and the growth in the world population consumption of the energy over the world, the FA has significantly increased. Thus, air and environmental pollution became a problem, then; the idea of

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Table 1
Chemical analysis and physical properties of PC, FA and BFS (%)

Component	PC (%)	FA (%)	BFS (%)
SiO_2	19.80	30.6	39.56
Fe_2O_3	3.42	5.5	0.33
Al_2O_3	5.61	14.8	10.82
CaO	62.97	36.8	37.68
MgO	1.76	2.5	6.79
SO_3	2.95	4.9	0.33
Chloride (Cl^-)	0.04	–	0.125
Undetermined	0.30	–	3.99
Free CaO	0.71	11.5	–
LOI	0.36	2.4	–
Specific gravity (g/cm^3)	3.15	2.4	2.86
Specific surface (cm^2/g)	3410	3200	4000
Compressive strength (MPa)			
2 days	24.5	–	–
7 days	42.0		18
28 days	44.4		

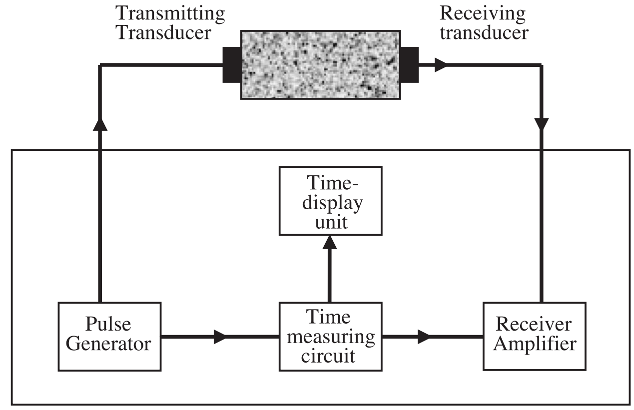

Fig. 1. Schematic diagram of pulse velocity testing circuit.

using waste material has gained popularity. FA and BFS are the most common concrete ingredients due to their pozzolanic properties [18,19].

There are many studies related to the UPV; for example, Tharmaratnam and Tan [20] provided the empirical formula of the combined UPV and ultrasonic pulse amplitude (UPA). Liang and Wu [21] studied theoretical elucidation of the empirical formulae for the UPV and UPA and combined methods. Ye et al. [22] determined the development of the microstructure in cement-based materials by means of numerical simulation and UPV. However, the relationship between the UPV and compressive strength of mineral-admixtured concrete has not been investigated. This study focused on the relationship between compressive strength of mineral-admixtured concrete and UPV.

2. Experimental study

ASTM Type I [23] Portland cement (PC) from Set cement factory in Ankara, Turkey was used in this study. FA, BFS and aggregate were obtained from Afşin Thermal Power Plant, İskenderun Iron-Steel Factory in Hatay-İskenderun and Aras River in Erzurum in Turkey, respectively. The chemical composition and physical properties of the mineral admixtures used in this study are summarized in Table 1.

Zero percent, 50%, 60% and 70% FA or BFS were used in replacement of PC. In addition, 25% FA + 25% BFS, 30% FA + 30% BFS and 35% FA + 35% BFS also replaced PC. Mix proportions are given in Table 2.

For each mixture, three samples of 200-mm-high and 100-mm-diameter cylinders were prepared and stored in lime-saturated water at 20 ± 3 °C until the time of the testing. The samples were tested at 3, 7, 28 and 120 days for UPV and compressive strength in accordance with ASTM C 597-83 [24] and ASTM C 39 [25], respectively. A schematic diagram for UPV is shown in Fig. 1. Statistical regression analyses were performed by Microsoft Excel programme.

3. Results and discussions

The results obtained in the tests are shown in Table 3 and Figs. 2–11. They are evaluated and discussed below.

Table 2
Mix proportions

Mixtures	Control samples	FA (%)			BFS (%)			FA + BFS (%)		
		50	60	70	50	60	70	25 + 25	30 + 30	35 + 35
w/c	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Water (kg/m^3)	167.5	167.5	167.5	167.5	167.5	167.5	167.5	167.5	167.5	167.5
Cement (kg/m^3)	350	175	140	105	175	140	105	175	140	105
Fly ash (kg/m^3)	–	175	210	245	–	–	–	87.5	105	122.5
Blast furnace slag (kg/m^3)	–	–	–	–	175	210	245	87.5	105	122.5
Aggregate sizes (mm)										
0–4 kg/m^3	740	740	740	740	740	740	740	740	740	740
4–8 kg/m^3	458	458	458	458	458	458	458	458	458	458
8–16 kg/m^3	577	577	577	577	577	577	577	577	577	577
Superplasticizer (%)	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8

Table 3
Hardened concrete properties

Samples	Control samples	FA (%)			BFS (%)			FA + BFS (%)		
		50	60	70	50	60	70	25 + 25	30 + 30	35 + 35
3-day Compressive strength (MPa)	27.9	8.6	4.5	2.4	9.0	7.5	4.9	10.5	7.3	5.4
3-day UPV (m/s)	4060	3460	2980	2720	3460	3510	3330	3750	3570	3450
7-day Compressive strength (MPa)	38.1	13.7	9.1	4.5	20	17.8	15.1	18.4	16.2	11.6
7-day UPV (m/s)	4270	3780	3580	3270	3940	3950	3980	3990	3800	3760
28-day Compressive strength (MPa)	43.6	20.9	13.8	9.7	35	32.3	26.4	33.4	30.9	25.3
28-day UPV (m/s)	4310	3990	3910	3640	4200	4230	4110	4260	4160	4080
120-day Compressive strength (MPa)	54.6	35	31.3	27.4	50.2	45.4	37.4	41.9	35.3	34.7
120-day UPV (m/s)	4470	4140	4140	4070	4280	4340	4250	4230	4220	4150

3.1. Compressive strength and UPV

The compressive strength and UPV results of the concretes made with mineral admixtures were determined at 3, 7, 28 and 120 days.

3.1.1. The effect of FA on the compressive strength and UPV

Table 3 shows that FA reduced compressive strengths of the concretes at all levels of replacement at 3, 7, 28 and 120 days. Reductions were 69%, 84% and 91% due to 50%, 60% and 70% FA replacement of PC at 3 days, respectively. The reductions due to FA replacement at early ages increased with the increase of FA level and decreased with the curing time. The reductions were 64%, 76% and 88% due to 50%, 60% and 70% FA replacement of PC at 28 days, respectively. The observations on the strength development of FA concrete are similar to those for the FA-modified cement mortars at the same water/binder ratio [26].

Reduction values decreased with the increasing curing period, and at 120-day curing period, reductions were 36%, 43% and 50% at 50%, 60% and 70% FA replacements, respectively. Demirboga [26] reported similar results for mortars at 50% and 70% FA replacements. Thus, it can be said that the mortar containing FA showed a steady reduction in strength for the early curing period as a function of replacement percentage, which can be directly related to the properties of FA that decreases the heat of hydration of concrete and needs a long curing period. The results of numerous studies have indicated that FA slows the rate of hardening and reduces the early compressive strength of concrete [27,28] and mortars [26].

It can be seen from Fig. 2 that UPV values decreased with increasing FA replacement for PC at the 3-, 7-, 28- and 120-day curing periods. Maximum reduction occurred at 70% FA replacement and it was 33%, 23%, 16% and 9% at the 3-, 7-, 28- and 120-day curing periods, respectively. Minimum reduction occurred at 50% and 60% FA for 120-day curing period. The UPV values decreased with increasing FA replacement percentage. However, reduction in UPV values due to FA replacement was much lower than that of compressive strength. The higher the FA replacement, the higher the decrease in UPV values, especially at early ages.

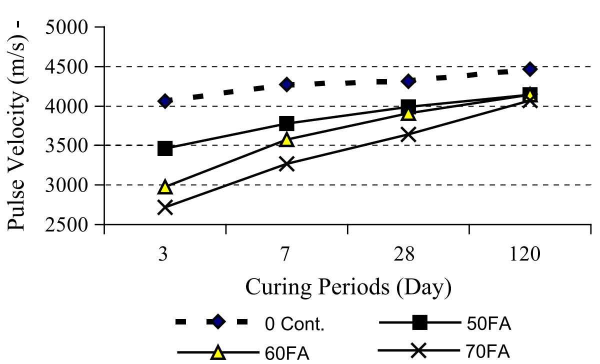

Fig. 2. Relationship between UPV and different curing periods for FA.

3.1.2. The effect of BFS on the compressive strength and UPV

BFS also induced the compressive strengths of the concretes to reduce at all levels of replacement at 3, 7, 28 and 120 days. However, reductions due to BFS were lower than those of FA for all replacement levels of BFS and at all curing periods. Compressive strength decreased with increasing BFS replacement ratio and increased with curing time. For 50% BFS replacement, compressive strength was approximately similar to the control sample's compressive strength. The compressive strength of BFS concretes was very low at early ages and similar to that of FA concretes, but with the increase of curing time, it dramatically reduced. Reductions were 68%, 73% and 82% for 50%, 60% and

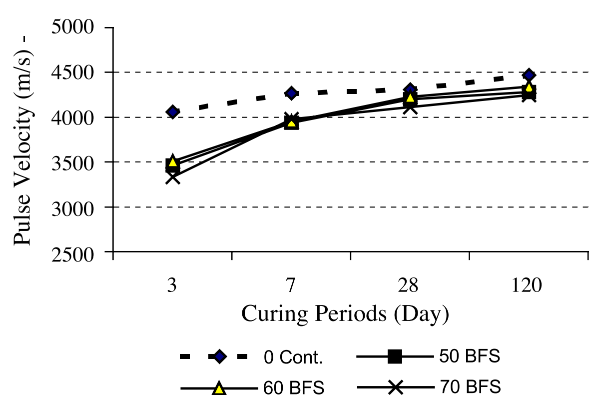

Fig. 3. Relationship between UPV (m/s) and different curing periods (day) for BFS.

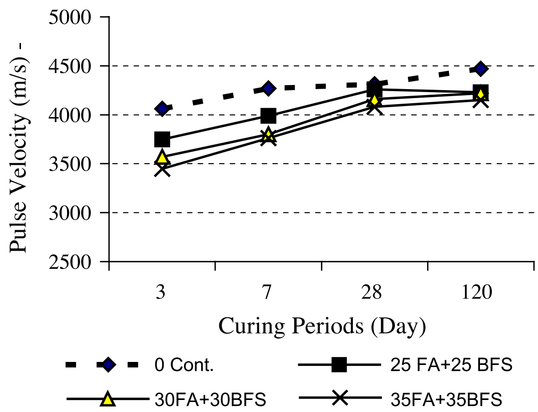

Fig. 4. Relationship between UPV (m/s) and different curing periods (day) for FA + BFS.

70% BFS replacement, respectively, at the 3-day curing period but it reduced to 8%, 17% and 32% for 50%, 60% and 70% BFS replacement, respectively, at 120-day curing period. Reductions at early ages due to BFS may be due to the low heat of hydration of BFS. Tasdemir et al. [29] reported that BFS concretes tend to be weaker at early ages than ordinary PC concretes, but at later ages, they may have even more strength than the ordinary PC ones. Reeves [30] has shown that in the use of BFS, the heat of hydration is slower than that of the ordinary PC. Thus, the rate of gain of strength is also slower than that of ordinary PC [31].

The UPV of BFS for 3, 7, 28 and 120 days is shown in Fig. 3. UPV changed between 3330 and 4060 m/s at the 3-day curing period. Fifty percent, 60% and 70% BFS replacement for PC were lower than that of control sample, but with the increasing curing period, the reduction due to BFS in UPV decreased. Maximum UPV value was determined for control sample at all curing ages. UPV values decreased with increase of BFS as it occurred for FA. However, after about the 28th day curing period, the UPV reached a certain value and thereafter increased only slightly. In other words, the UPV took a shorter time to reach a plateau value for high-volume mineral-admixtured concretes when compared to the compressive strength. The increment in UPV due to BFS was higher than that of FA for curing period.

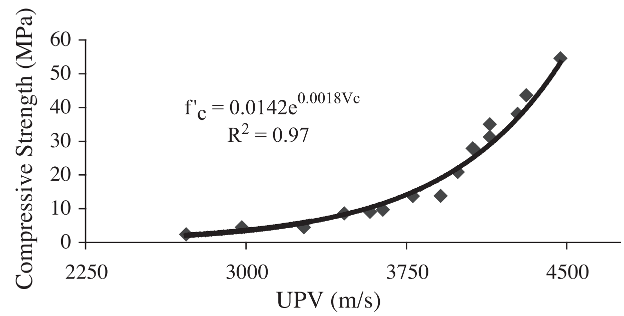

Fig. 6. Relationship between compressive strength and UPV for samples containing FA.

3.1.3. *The effect of FA+BFS on the compressive strength and UPV*

It can be seen from Table 3 and Fig. 4 that FA + BFS decreased the compressive strength. However, reductions were lower than those of FA and BFS at 25%FA + 25%BFS and 35%FA + 35%BFS for the 3-day curing period. For the other curing periods, reductions were higher than those of BFS but lower than those of FA. At the 7- and 28-day curing periods, compressive strengths of FA + BFS were similar to those of BFS. For the 120-day curing period, compressive strength of 50%BFS was 17% higher than that of 25%FA + 25%BFS. Increasing age decreases the gap between the strength of control sample and the other samples. This is due to the pozzolanic activity of minerals that may be effective only in the long term. It can be seen from Table 3 that concretes made up of high-volume FA + BFS can be used for C 25 (strength class, MPa) up to 35%FA + 35%BFS replacement of PC. Its disadvantage is due to increasing the molding time.

The UPV of FA + BFS for 3, 7, 28 and 120 days is shown in Fig. 4 and Table 3. UPV changed between 3750 and 3450, between 3990 and 3760, between 4260 and 4080, and between 4230 and 4150 m/s at the 3-, 7-, 28- and 120-day curing period, respectively. UPV values decreased with increasing FA + BFS as it occurred for compressive strength. However, the gap between UPV values was much lower than those of compressive strength. With the increasing curing period, the reduction due to FA + BFS in UPV

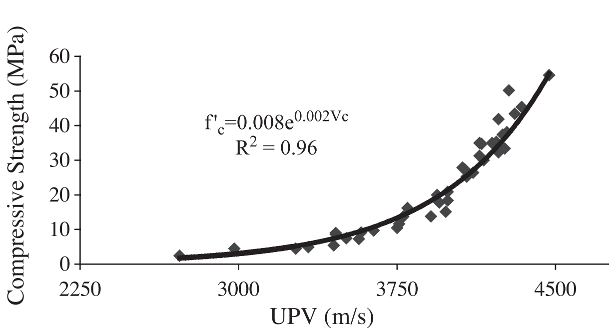

Fig. 5. Relationship between UPV and compressive strength for all results between 3 and 120 days of curing periods for FA, BFS and FA + BFS.

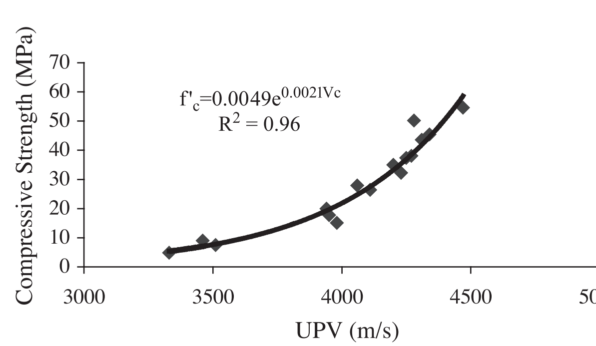

Fig. 7. Relationship between compressive strength and UPV for samples containing BFS.

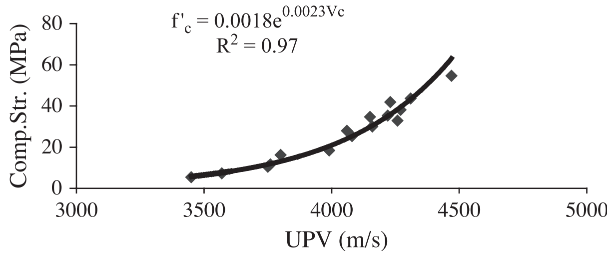

Fig. 8. Relationship between compressive strength and UPV for samples containing FA + BFS.

decreased, and at the 120-day curing period, UPV values of FA + BFS was similar. At the 3-day curing period, UPV values were higher than those of FA and BFS, separately; replacement of PC as the same result were determined for compressive strength. For the other curing periods, there was no significant gap in the UPV values of concretes made up of BFS and FA + BFS.

3.2. Relationship between compressive strength and UPV

The UPV method, also known as the transit time method, uses a detector to measure the time of flight it takes for an ultrasonic pulse to pass through a known thickness of solid material. The UPV can be written as:

$$V_c(x,t) = \frac{x}{t} \tag{1}$$

where, V_c (x, t) is the UPV in concrete, x is the propagated path length and t is the transit time.

Based on the experimental results, Tharmaratram and Tan [20] gave the relationship between UPV in a concrete V_c and concrete compressive strength f_c' as:

$$f_c' = ae^{bV\mathrm{c}} \tag{2}$$

Taking into account the heterogeneous nature of concrete, the general relationship between UPV and compressive strength is pooled together for all results in Fig. 5 for concretes at ages between 3 and 120 days. There was a very good exponential relationship between UPV and compressive strength. Because R^2=.96, we can say that 96% of the variation in the values of compressive strength is accounted for by exponential relationship with UPV (see Fig. 5). For all results, we found the following law relating compressive strength (f_c' in MPa) to UPV (V_c in m/s):

$$f_c' = 0.008e_c^{0.002V} \tag{3}$$

The relationship determined in this study, between f_c' and V_c, fitting the general Eq. (2) was reported by Tharmaratram and Tan [20].

Figs. 6, 7 and 8 show results of high-volume FA, BFS and FA + BFS, separately. For the FA, BFS and FA + BFS, we found the below models, respectively:

$$f_c' = 0.0142e_c^{0.0018V} \tag{4}$$

$$f_c' = 0.0049e_c^{0.0021V} \tag{5}$$

$$f_c' = 0.0018e_c^{0.0023V} \tag{6}$$

FA, BFS and FA + BFS models justify the general model of Eqs. (2) and (3) and their determination coefficients were .97, .96 and .97, respectively.

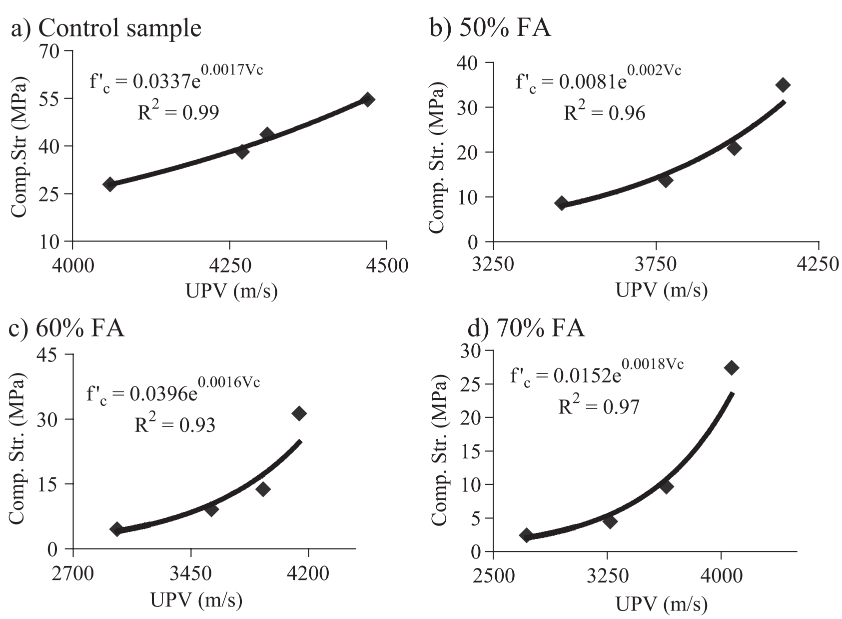

Fig. 9. (a–d) Relationship between compressive strength and UPV for samples containing FA separately.

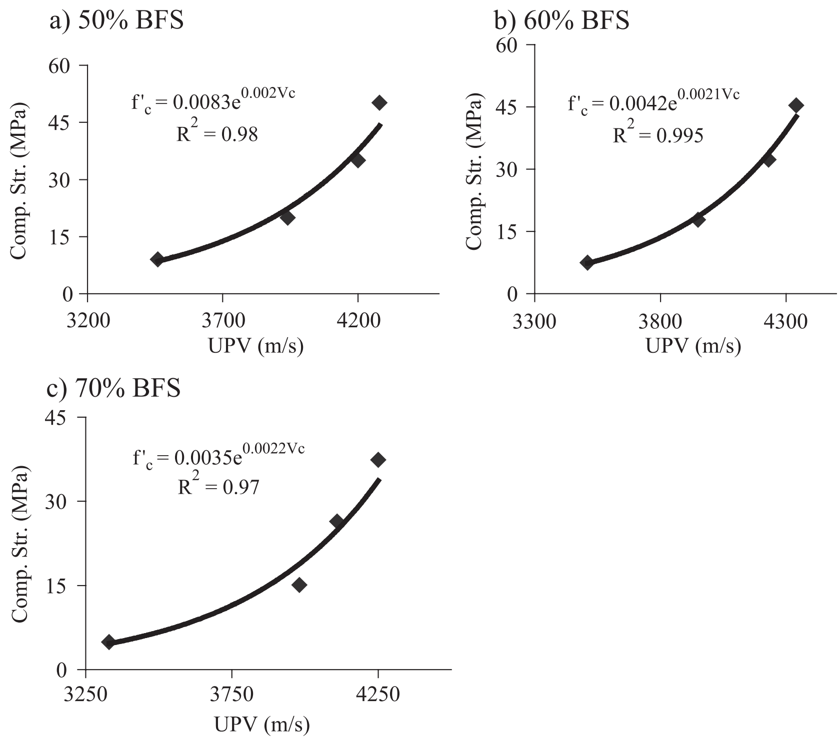

Fig. 10. (a–c) Relationship between compressive strength and UPV for samples containing BFS separately.

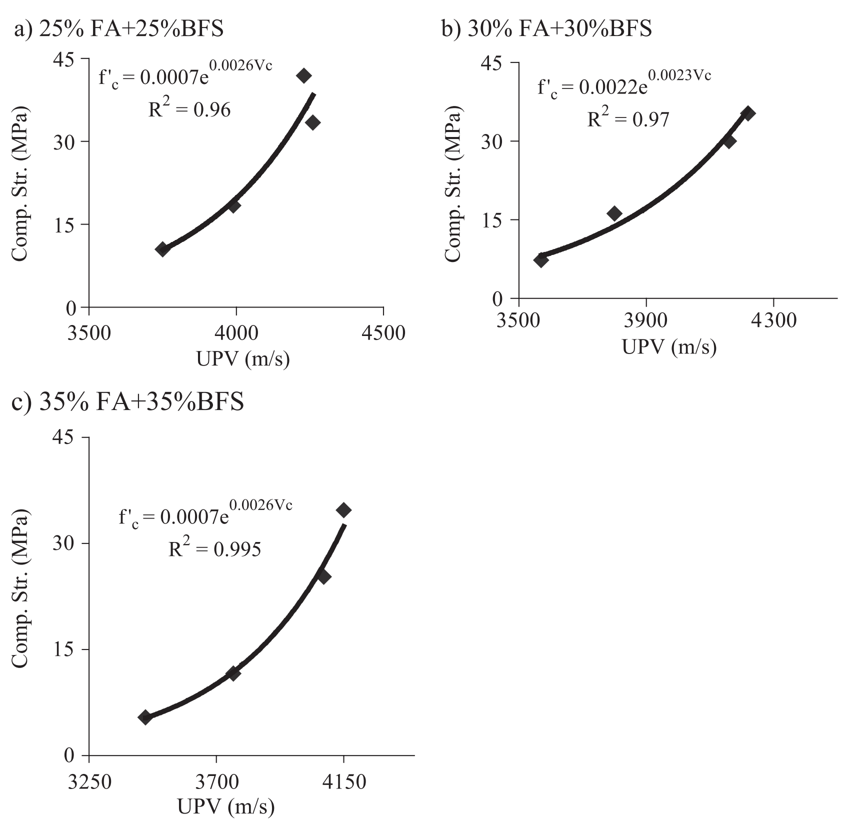

Fig. 11. (a–c) Relationship between compressive strength and UPV for samples containing FA + BFS separately.

When models of 50%, 60% and 70% FA, separately, were pooled, we found that the relationships were also exponential (see Fig. 9a–d). Determination coefficients of 0%, 50%, 60% and 70% FA were .99, .96, .93 and .97, respectively. Zero percent, 50%, 60% and 70% FA replacement of PC corroborated Eqs. (2), (3) and (4). Models are similar but the constants are different from those of Eqs. (2), (3) and (4).

In all levels of BFS, relationships between UPV and compressive strength were also exponential and determination coefficients of 50%, 60% and 70% BFS were .98, .995 and .97, respectively (see Fig. 10a–c). Each BFS model was similar to the general model for concrete reported by Tharmaratram and Tan [20] and similar to both models determined here for all mineral admixtures, Eq. (3), and model of FA, Eq. (4), that was pooled together. The equations of the models of BFS are shown in Fig. 10 a–c.

Separately, 25%FA + 25%BFS, 30%FA + 30%BFS, and 35%FA + 35%BFS's models were the same as that of all together of FA + BFS, Eq. (6), and general model, Eq. (2). There was no difference in the models among 25%FA + 25%BFS and the other percent replacement of PC but there was difference in the constant values of the equations (see Fig. 11a–c).

It can be seen from Fig. 11a and c that their constants are also similar but the constant of Fig. 11b is different from them. Constants of Fig. 11a and b changed between 0.0007 and 0.0022 and between 0.0023 and 0.0026, respectively.

It can be concluded that this study corroborated that the general Eq. (2) reported by Tharmaratram and Tan [20] are also fitted for mineral-admixtured concretes.

4. Conclusions

1. High-volume FA replacement induced to reduction in compressive strength at all levels of replacement. The gap in the compressive strength was very high at early age, but with increasing curing period, the gap decreased. UPV values also increased with the increasing curing period for FA samples. Maximum reductions occurred for 70% replacement of FA.
2. The maximum compressive strength and UPV were observed with the control samples. Both compressive strength and UPV were very low for all levels of mineral admixture at early-age curing period, especially for samples containing high-volume FA. However, with the increase of curing period, both compressive strength and UPV of all samples increased. BFS also caused the reduction of compressive strength and UPV at all curing periods. However, the gap due to BFS was lower than that of FA for each curing period and each replacement percent.
3. The increment in the compressive strength due to curing period was higher than that of UPV for all mineral admixtures.
4. FA + BFS reduced both compressive strength and UPV values. However, reductions were lower than that of FA and higher than that of BFS.
5. A determination coefficient (R^2) of .96 indicates a very good exponential relationship between UPV and compressive strength when all results pooled together.
6. When compressive strength and UPV values of FA, BFS and FA + BFS results were pooled together separately, the relationships were exponential and only constants were different for each mineral.
7. The same model was determined for each replacement percent for all FA, BFS and FA + BFS replacements. It can be concluded that relationship between compressive strength and UPV is also exponential for mineral-admixtured concrete.

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